Ethanol and Internal Combustion Engines

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1. Introduction.

Increasing use of ethanol as an automotive fuel in the United States has generated a lot of questions concerning the effect of ethanol-gasoline blends on spark ignited internal combustion engines. This paper will attempt to clear up confusion surrounding:

Low ethanol blends (E10, E15)
E85 and how flex fuel vehicles handle high ethanol blends
How electronically controlled fuel injection systems in modern automobiles adapt to different fuel blends
The impact of ethanol blending on small engines, marine engines and classic automobiles with carbureted fuel systems.

This paper contains a lot of technical material. It is organized so that the reader can skip over material that s/he is already familiar with. The organization of this document is as follows:

Section 2: provides background material concerning ethanol as an automotive fuel. This section briefly describes what ethanol is, how it chemically relates to gasoline, and a brief history of ethanol use in automobiles.
Section 3: contains overview material about the operation of a modern, 4 stroke, electronically controlled fuel injected (EFI) engine for readers who are not familiar with engine operation. The 4 stroke (Otto cycle) operation is explained, along with the important engine parameters of air/fuel mixture control and ignition timing.
Section 4: describes the modes of EFI engine operation in some depth, focusing on open and closed loop modes of engine operation. Closed loop adaptation of the EFI engine to differing fuels is explored in some detail. Closed loop ignition timing schemes are also mentioned.
Section 5: describes the effects that ethanol blends have on an EFI engine, both in closed loop and open loop modes of operation. It details the issues raised about ethanol on non-flex fuel vehicles and provides the factual information about the validity of these issues in technical terms. This section also mentions how flex fuel engines deal with these same issues, the special provisions of flex fuel engines to deal with high ethanol blends, and how aftermarket conversion kits operate to allow non-flex fuel vehicles to run on high ethanol blends (e.g. E85).
Section 6: briefly deals with the issues surrounding non-EFI engines; particularly small 2 stroke engines (lawn mowers, leaf blowers, etc.), marine engines and classic automobiles with carbureted engines.
Section 7: summarizes the material presented in this paper.

2. Background and History

2.1. Liquid Fuels for Internal Combustion Engines.

Ethanol, also known as Ethyl Alcohol, is a light volatile liquid. It is a member of the family of organic compounds collectively known as alcohols. The alcohols all contain a chain of carbon atoms surrounded by hydrogen atoms except for one bonding site, where the carbon atom is bonded to an oxygen atom, which in turn is bonded to a hydrogen atom (the combination of the oxygen atom and hydrogen atom is also referred to as a "hydroxyl group"). See: http://en.wikipedia.org/wiki/Ethanol for further detail.

Ethanol is the member of the alcohol family that has two carbon atoms. Other members of the alcohols that are often associated with automotive fuel applications are: methanol (one carbon atom, also called "wood alcohol"), propanol (three carbon atoms, often familiar in the form of isopropyl alcohol, better known as "rubbing alcohol") and butanol (or isobutanol).

Ethanol is the drinking alcohol. It is the alcohol found in beer, wine and distilled spirits. The production of ethanol via yeast fermentation of sugars and starches into beer and wine has been known since ancient times. These beverages contain up to around 14% ethanol (the rest being water, some dissolved solids, other alcohols and other organic compounds – "congeners" to beverage distillers). Distilled spirits are produced from a "beer" via the process of distillation, which enriches the ethanol content by exploiting the fact that ethanol boils at a lower temperature than does water.

Gasoline is a mixture of hydrocarbons. The hydrocarbons are very similar, chemically, to the alcohols, except that the hydrocarbons do not contain any oxygen atoms. Ideal gasoline would be a single molecule with eight carbon atoms, or "octane". In reality, gasoline is a blend of hydrocarbons containing between four and twelve carbon atoms. The "octane rating" of a motor fuel is an index of the fuel's ability to resist pre-ignition, or engine knock, and is based upon the anti-knock properties of pure octane being equal to 100. Since gasoline is inherently a blend of different hydrocarbons, which will ignite at different temperatures and pressures and burn at different rates, the octane rating of gasoline fuels is less than 100. Regular gasoline is the least refined (the greatest mixture of different hydrocarbons) and generally has an octane rating of around 86. Midrange and premium gasoline is more highly refined to contain a higher percentage of octane, raising their octane rating to around 92. While alcohol fuels do not contain any octane molecules, they can have a measurable octane rating. Pure ethanol has an octane rating of around 116. When blended with regular unleaded gasoline, ethanol boosts the fuel's overall octane rating. Engine operation and knocking is discussed further in section 3 of this paper.

The operation of an internal combustion engine is based upon explosive burning of a liquid fuel in air. Burning requires free oxygen atoms which, in this case, are drawn from the air. Because the alcohols already contain an oxygen atom in the molecule, a molecule of alcohol can be thought of as being "partially burned". Therefore, burning an alcohol produces less energy per unit volume of the fuel than does burning a hydrocarbon. The hydrocarbons do not contain any oxygen atoms and all of the carbon and hydrogen atoms are therefore available for burning (carbon ideally combines with oxygen to form carbon dioxide, CO2, while hydrogen ideally combines with oxygen to form water vapor, H2O). Since the alcohols all contain a single oxygen atom, the larger alcohol molecules have more free carbon and hydrogen atoms to burn than do the smaller alcohol molecules. Ethanol produces about 36% less heat energy per gallon than does gasoline, while methanol (the smallest alcohol molecule) produces about 50% less heat energy per gallon than does gasoline. In contrast, butanol produces only about 10% less heat energy per gallon than does gasoline. However, heat energy is not the desired end product of burning a liquid fuel in an internal combustion engine; mechanical energy is. Internal combustion engines derive mechanical energy by absorbing some of the heat released in burning to create pressure on a piston. The alcohols are much more efficient at doing this than is gasoline. As a consequence, engines running on alcohol fuels may run as high as 40% efficiency (conversion of heat to mechanical energy) whereas gasoline runs only about 23% efficiency. Cars running on a proper air/fuel mixture of ethanol tend to lose only about 15% - 20% fuel mileage as compared to gasoline. If the ignition timing and engine compression ratios are changed to exploit the superior octane rating of the alcohols, it is possible to actually increase the fuel mileage over gasoline (albeit, high compression engines will be not able to run on gasoline).

2.2. History of Ethanol as a Motor Fuel.

This section provides a brief overview of the use of ethanol a motor fuel in automobiles. A more complete history can be found at: http://www.runet.edu/~wkovarik/papers/fuel.html.

The industrial revolution began with the advent of the high pressure steam engine. The steam engine is a form of *external combustion engine*, so called because the burning of the fuel to produce heat is performed externally to the conversion of heat into mechanical energy. Steam engines used well known and plentiful solid fuels, principally wood and coal. A steam engine burns the solid fuel to produce heat. The heat then boils water into high pressure steam and the steam pressure moves a reciprocating piston to produce mechanical energy.

While fuel for steam engines was plentiful and available, lubricants were not. Prior to the industrial revolution, animal and vegetable oils and fats were used as lubricants. The industrial revolution created an explosion in whaling to produce the needed oils and fats to lubricate the new machines. Lubricants became scare and the price became high. The discovery of crude oil in western Pennsylvania rapidly remedied this situation, as the heavier components of crude oil could be extracted and used for oil and grease. The lighter liquid components were found to make excellent and inexpensive lamp oil (kerosene), rapidly replacing the candles, vegetable oils and coal oil that was used previously. The very lightest and most volatile liquid components of crude oil refining (gasoline) had no original value and were waste products, as were the gaseous components (natural gas). The latter had to be flared off in order to avoid the danger of explosion.

The internal combustion engine was invented later in the industrial revolution, principally as a solution for transportation needs. While steam engines ran railroads and ships, the need to access large amounts of water made the steam engine impractical for smaller, land based vehicles. The internal combustion engine required readily available volatile liquids for fuel. At the onset, the only such fuel was ethanol. Ethanol, as the drinking alcohol, had been produced on farms from time immemorial as a safe drink (the alcohol killed harmful bacteria), a solvent, a household sterilizer, a cooking and lighting fuel, and a means to preserve excess food product that would otherwise rot. The first automobiles thus ran on ethanol. After crude oil production and refining ramped up, gasoline became a competitor. As a waste product, it could be sold very cheaply. The major cost was getting gasoline to the consumer, as most early automobiles and tractors were sold into rural areas, whereas gasoline was refined near the source. There is a very colorful history about the conflict between ethanol fuel advocates (such as Henry Ford) and gasoline advocates (principally the oil man, John D. Rockefeller). The history is complicated by two facts: (1) concerns that the supply of crude oil would run out (a major conjecture prior to the discovery of large amounts of crude in east Texas), and (2) the need for ethanol as an octane booster (prior to the introduction of lead as an octane booster for gasoline). The colorful history came to an end with prohibition, which banned the production of ethanol for all uses, although human consumption was the official target. Interest in ethanol fuel for automobiles resumed in the 1970s with OPEC and the Arab oil embargo, and with the removal of lead from gasoline for health reasons.

Ethanol continued to be used as a motor fuel sporadically between the 1920s and 1980s whenever gasoline was in short supply. Germany ran most private automobiles on ethanol made from potatoes in World War II. When oil prices rose dramatically in the 1970s, interest in alcohol fuels picked up in the United States and elsewhere. The nation of Brazil, struggling over a mountain foreign debt from oil imports, made a major commitment to producing ethanol as an alternative motor fuel. Brazil rapidly became the world's largest producer of ethanol and mandated ethanol pumps at every petrol station in the country. The California Energy Commission took interest in methanol as an alternative motor fuel and worked with Ford Motor Company and other auto manufacturers to evaluate methanol powered cars. The California program resulted in the invention of the modern flex fuel vehicle by engineers at Ford, albeit Henry Ford's original model T's were manually-adjusted "flex fuel" cars right up until prohibition (owing to Henry Ford's belief that he couldn't expect his rural customers to buy his product – cars - if he didn't offer to buy their product – ethanol). In 2007, the United States surpassed Brazil in ethanol production and by 2010 the USA produced nearly 50% more ethanol than second place Brazil.

2.3. Liquid Fuel Blends.

The emphasis today is on blending gasoline and ethanol for an automobile fuel. In the 1980s, the EPA mandated that automobile fuels be "oxygenated" in order to reduce air pollution. Since alcohols contain oxygen, interest

renewed in ethanol as an oxygenate. In addition, removal of lead from gasoline renewed interest in ethanol as an octane booster. There are alternatives to ethanol for both of these needs. The oil industry originally pushed MTBE as an oxygenate, but it was phased out after discovery that it was causing water pollution problems.

Today, emphasis has shifted to renewable fuels and the US Government has set a renewable fuel standard to be achieved by 2020. Ethanol is not the only contender for a renewable motor fuel, but its long history, familiarity, low cost and the low level of technology needed to produce it has made it the preeminent contender. Since the late 1980s, the US EPA has certified a blending of 10% ethanol in regular unleaded gasoline; the so-called "E10" product. All new cars sold in the USA beginning with the 2001 model year are required, by law, to be warranted to run on blends up to E10. As of this writing, the EPA has adopted an E15 standard (15% ethanol, 85% gasoline) for all cars built in model year 2001 and later. The EPA certification testing also includes small, 2 stroke engines and marine engines.

While E10/E15 is intended for all automobiles, a blend called "E85" is intended for flex fuel vehicles. E85 is nominally 85% ethanol and 15% gasoline, albeit it can be as high as 30% gasoline in cold climates in winter. The principle reason for blending some gasoline into ethanol for flex fuel vehicles is to improve starting in cold weather. The USA and the EU have adopted E85 as the standard, whereas Brazil has an E100 (pure ethanol) standard.

There is a lot of confusion surrounding E85 and automobiles, particularly in the area of wet or "hydrous" alcohol. As described briefly above, ethanol is separated from the water in which it is produced via a process called distillation. The distillation process does not remove all of the water. Having some water mixed in with the fuel is actually improves performance of an internal combustion engine, as the water provides extra mass to absorb the heat of combustion and turn it into high pressure steam for mechanical energy. Research on internal combustion engines has shown that ethanol as low as 160 proof (80% ethanol, 20% water) works very well in automobile engines designed to run on alcohol. However, water and gasoline don't mix well (are not "miscible", in chemical terms), so the water must be removed when producing ethanol-gasoline blends. This dry or "anhydrous" ethanol is needed to prevent phase separation of the fuel components in ethanol - gasoline blends. This is a particular concern for the small and marine engine market, and is discussed further in section 6, below.

3. Operation of the Automobile Engine.

This section provides a basic description of the operation of the electronically controlled fuel injected (EFI) automobile engine. This type of engine is found on virtually every car built for sale in the United States in the last 20+ years.

Automobile manufacturers introduced the EFI engine in the 1980s, in response to US Government mandates for improved fuel economy and reduced tailpipe emissions. The manufacturers determined that the only way to meet these dual requirements was with an EFI engine. This engine design utilizes an electronic control unit (ECU) and various sensors in the engine to optimize engine operation dynamically. The ECU can adapt engine operation to mechanical changes and degradation of mechanical components with time, as well as to changes in fuel and other factors. The ECU is a digital computer (more correctly, a *microcontroller*) that monitors sensor data hundreds of times per second and makes adjustments to fuel mixture and ignition timing, based upon engine operating conditions, driver demand and data from the sensors.

Automobile manufacturers provide their own, sometimes unique, variations on basic engine design. To keep this discussion simple and on point, only a basic and generic description of automobile engine components and operation is provided.

3.1. Four Stroke Engine Basic Operation.

All modern spark ignited (non-diesel) automobile engines utilize the "Otto cycle" (some hybrids use a variation called the "Atkinson cycle"), or four stroke operation. This section provides a textual summary of this operation. More detail, including animated diagrams, can be found at: http://auto.howstuffworks.com/engine1.htm.

The automobile engine begins life as a block of metal with cylindrical holes cast or bored through it. These holes are, appropriately enough, called the *cylinders*. Each cylinder has a solid cylinder of metal fitted into it called the *piston*. The piston is just slightly smaller in diameter than the inside of the cylinder so that the piston can slide up and down smoothly within it. The piston is fitted with circular *piston rings* around the piston body to create a gas tight seal between the top of the piston and the cylinder.

A rotating shaft called the *crankshaft* runs through the bottom of the engine block. The crankshaft is so called because the shaft is shaped like a crank beneath each piston. A *connecting rod* is attached to the underside of each piston via a pivot. The bottom of the connecting rod is attached to a crank on the crankshaft via a bearing. Rotating the crankshaft causes the piston to move up and down in the cylinder. Conversely, pressing down on the top of the piston when it is high in the cylinder causes the crankshaft to rotate, until the piston is all of the way down in the cylinder.

Each cylinder is closed off at the top with a metallic *cylinder head*, creating a sealed chamber between the top of the piston and the top of the cylinder. Two valves are fitted into the cylinder head: the *intake valve* and the *exhaust valve*. These values are operated off of a *camshaft* that controls opening and closing of the valves. The camshaft is mechanically linked to the crankshaft so that the valves open and close at the proper points in the cycle of the engine.

The cylinder head is also fitted with a tapped hole into which is screwed a *spark plug*. The spark plug produces an electrical spark when fired off by the computerized engine control unit (ECU). The business end of the spark plug protrudes into the cylinder so that the spark can ignite a mixture of fuel and air in the cylinder.

The Otto cycle engine operates in four up/down *strokes* of the pistons in the cylinders, as follows:

> *Intake Stroke*: The intake valve is opened as the crankshaft pulls the piston downward in the cylinder. The suction caused by this action pulls a mixture of vaporized fuel and air into the cylinder from the *intake manifold*. The engine supplies power via the crankshaft to implement this stroke.
> *Compression Stroke*: Both valves are closed. The crankshaft pushes the piston up in the cylinder, compressing the air/fuel mixture. The compressed mixture of gasses heats up due to the increased pressure but does not ignite. The engine supplies power via the crankshaft to implement this stroke.
> *Power Stroke*: Both valves remain closed. The spark plug fires off and ignites the compressed air/fuel mixture. The resulting detonation of the fuel releases a great deal of heat and converts the fuel/air mixture to burned exhaust gasses (ideally, CO2 and H2O). The exhaust gasses absorb some of the heat of combustion and rapidly expand, forcing the piston down in the cylinder. This is the only stroke where the piston drives the crankshaft and is the source of the power from the engine.
> *Exhaust stroke*: The crankshaft pushes the piston back up in the cylinder while the exhaust valve opens. The spent exhaust gasses are forced out of the cylinder into the exhaust manifold and ultimately expelled out the car's tailpipe via the exhaust system. The cycle then repeats with the next intake stroke.

Since power is only produced during the power stroke, an automobile engine typically has at least four cylinders. The cylinders go through the four strokes in a staggered fashion so that at least one cylinder is in the power stroke at all times. A heavy flywheel is also attached to the crankshaft to smooth its rotation between firing cycles of the engine. The crankshaft supplies power out of the engine, to the *drive train* and ultimately the car's wheels.

3.2. Electronically Controlled Fuel Injection.

A precisely controlled mixture of fuel and air must be provided into the intake manifold for the intake stroke of each cylinder. It was noted in section 2, above, that burning the fuel requires free oxygen from the air. Each atom of carbon in the fuel needs to combine with two atoms of oxygen (to form carbon dioxide - CO2) and each pair of hydrogen atoms in the fuel must combine with one oxygen atom (to form water vapor - H2O). CO2 and H2O are the ideal exhaust gasses from burning an organic fuel. Obviously, for any given type of fuel, there exists an ideal ratio of air to fuel where precisely enough oxygen atoms are present to combine with every single carbon and every single hydrogen atom; no more, no less. The technical name for this ideally perfect air/fuel ratio is the *stoichiometric* ratio. The stoichiometric ratio is different for each different type of fuel. The stoichiometric ratio for gasoline is around 14.7:1 (note: since gasoline is a mixture of different hydrocarbon molecules, the stoichiometric ratio is only approximate). The stoichiometric ratio for pure ethanol is approximately 9:1 and for E85, it is about 9.8:1. The reason for this difference in stoichiometric ratio is because ethanol is an oxygenated fuel, as explained in section 2, above.

An engine that is supplied with more fuel than is required by the stoichiometric ratio is said to be running *rich*. Conversely, an engine that is supplied with more air than is required by the stoichiometric ratio is said to be running *lean*. An overly rich mixture will not burn all of the fuel and will therefore be inefficient. It will lose power and have poor fuel economy, as well as produce an excess of the pollutants carbon monoxide (CO) and unburned hydrocarbons (particulates). A rich mixture will tend to make the engine run cool for two reasons: (1) not all of the fuel is burned, and (2) the excess liquid fuel will absorb heat from the cylinder in the process of evaporation. Conversely, leaning the mixture will generally cause the engine to heat up excessively near the stoichiometric ratio and then the power will fall off, engine efficiency will drop, and the engine will cool down as the mixture is leaned out further. Less mass in the fuel means less mass in the exhaust gasses that create mechanical energy by expanding when absorbing combustion heat.

Since the late 1970s, U.S. law has required automobile manufacturers to achieve high fuel efficiency standards while simultaneously keeping exhaust pollution low. Furthermore, the manufacturers are required to warrant pollution control limits for the life of the vehicle. Originally, the "life of the vehicle" was defined as 50,000 miles, but today the life is 150,000 miles or more. In order to meet all of these legal requirements as the engine components wear with age and use, the automobile manufacturers have decided that the engine cannot have fixed settings but must adjust to conditions and wear dynamically. Therefore, since the 1980s, all new cars sold in the United States have been fitted with electronically controlled fuel injection (EFI) systems.

A *fuel injector* is a small device through which liquid fuel flows whenever a valve is pulsed open via an electrical signal. The engine control computer, ECU, provides the necessary signals at the correct times. When the injector opens, fuel is forced though a very fine nozzle, like a perfume bottle "atomizer". This configuration sprays a very fine mist of fuel into the intake manifold of the engine. This misting of the fuel is necessary in order to vaporize it easily, so that the fuel and air can completely mix (the air is pulled into the intake manifold from the outside via an air filter). The ECU receives signals about the operator's intentions (throttle position), the engine's needs (manifold absolute pressure), engine speed and position, engine temperature, air mass pulled into the engine (compensating for altitude and ambient air pressure) through various sensors. The ECU uses these sensors to determine the precise timing of the pulsing of each fuel injector. The liquid fuel itself is forced from the fuel tank into the injectors (*fuel rail*) by a *fuel pump* located in or near the fuel tank. A *fuel pressure regulator* is used to regulate the fuel pressure to the fuel rail. Consequently, pulsing open a certain size fuel injector for a certain period of time precisely determines the amount of fuel injected into the intake manifold. The ECU computes the desired air/fuel ratio at each moment in time from the sensors mentioned above, and then computes the precise time to open the injectors to provide the necessary amount of fuel to the engine.

In order to compensate for engine component wear, changes in fuel composition, and other variable factors, modern EFI engines contain one or more *heated oxygen sensors* (HO2 sensors) in the exhaust system, just outside the engine. In spite of the common name, these sensors don't actually sense oxygen; they sense a factor called *lambda* which is the deviation (rich or lean) from stoichiometric ratio, as determined by the composition of the engine exhaust gasses. The highlighted text is very important in this discussion. The HO2 sensor determines the actual fuel mixture that was just burned in the engine in real-time, regardless of the type of fuel or the actual value of its stoichiometric ratio! This operation is key to understanding how a gasoline powered EFI engine responds to the presence of an alternative fuel, such as ethanol, with a different stoichiometric ratio. Section 5, below, carries this discussion forward.

3.3. Ignition Timing.

The operation of the ECU firing the spark plug was described in section 3.1, above. In order to achieve optimum engine performance, the pressure wave from the exploding fuel's exhaust gasses must hit top of the piston at the time when the piston is just a little past the top dead center of its travel. This causes the maximum pressure to build up on the piston because the cylinder volume is at its smallest. If the spark ignites the fuel too late, the piston will have been pulled down somewhat in the cylinder and the power stoke will operate off of less compression, reducing the power delivered to the engine from that power stoke. Conversely, if the spark ignites the fuel prior to the piston coming past top dead center of its travel, the pressure wave may press down on the piston while it is still being driven up in the compression stroke, causing severe power loss, as the fuel ignition now works against the engine for a short while in lieu of providing power to it. This latter condition is known as pre-ignition or "engine knock" and may damage the engine if it persists.

All modern EFI engines have a sensor that informs the ECU of the position of crankshaft or camshaft rotation dynamically, while the engine runs. The ECU's software uses tables (sometimes referred to as engine control "maps") to determine the correct timing of firing the spark plug, as well as the desired air/fuel ratio, given the instantaneous needs of the engine and its mode of operation (engine operating modes are discussed further in section 4). Note that it takes a short but finite time for the spark plug to ignite the air/fuel mixture in the cylinder and for the resulting pressure wave to hit the top of the piston. Thus, the spark must fire sometime before the piston is in the optimum position.

Modern automobile engines differ somewhat in how the ignition timing is controlled. Some engines just use data computed by the ECU from the map and from the engine position and speed sensors. Other engines actually have "knock sensors" that detect engine knocking and inform the ECU. These knock sensors, or similar sensors, allow the ECU to determine the precise ignition firing time dynamically, achieving superior performance when compared to a fixed setting in the map based only upon the engine design. Otherwise, ignition timing is programmed to be a little later (*retarded*) than optimal to ensure that knocking does not take place due to varying fuel mixtures (gasoline mixtures vary from tank to tank and with seasonal bends), engine wear, carbon buildup in the cylinders, etc.

4. Modes of Operation of the EFI Automobile Engine.

Automotive engineers design engines to operate in an optimal manner under varying modes of operation. Different manufacturers design and test engines to run under different real-world operating modes. This discussion is necessarily simplified and generic and focuses on three major modes of engine operation that are common to all automobile engines. The modes are: *normal operation*, *cold cranking*, and *wide open throttle* (WOT).

In normal operation, the ECU uses the heated oxygen (HO2) sensor(s) to control the air/fuel mixture to the engine dynamically. This is often referred to as *closed loop operation*. The other two modes of operation are *open loop*, in that the HO2 sensor is not involved and the ECU runs off of preset table values in its engine control map.

Understanding the difference between closed loop and open loop modes of engine operation is essential to understanding how a non-FFV engine will respond to the presence of ethanol or other alternative fuels, and how FFV ECU software differs from that of non-FFVs.

4.1. Normal Operation Mode.

The normal operation mode occurs when the engine is warmed up and the car is driven normally. In actuality, the engine does not have to be fully warmed up; it is only necessary that the heated oxygen sensor (HO2 sensor) is heated up to around 600 degrees, which is necessary for its proper operation. Once the HO2 sensor is heated up, the ECU goes into what is called *closed loop operation*. In closed loop operation, the ECU continuously monitors the HO2 sensor output and adjusts its pulsing of the fuel injectors in order to achieve the correct air/fuel ratio; that is, the desired value of lambda from its engine control map. As a general rule, the "correct" air/fuel ratio is a little on the rich side of the stoichiometric ratio. This setting minimizes pollution and optimizes performance, when used in conjunction with the catalytic converter and other emission control equipment on the vehicle. The value that the ECU uses to pulse the fuel injectors is known as the *fuel trim.*

What is important about closed loop operation is that the ECU does not need to adjust the fuel trim based upon values that are factory predetermined for a given engine and type of fuel. The whole idea is that the HO2 sensor feeds back data as to whether the engine is running rich or lean (the *lambda*) and the ECU dynamically uses this data to keep the engine running at an optimum level. This is the way that the manufacturer can guarantee to the EPA that the vehicle is performing its emission control functions optimally, even as gasoline blends change, ambient temperature and air pressure changes, and parts of the engine wear and degrade over the life of the vehicle.

The fuel trim is often split into two factors within the ECU. The *short term fuel trim* (STFT) is the instantaneous value that the ECU is using as it dynamically adapts to driving conditions. The *long term fuel trim* is a value that changes slowly (periods of 30 seconds to several minutes per change) and is reflective of changes in fuel mixture from tank to tank and degradation of engine components with time. The injector pulsing at any given time is based upon the sum of the STFT and LTFT. What generally happens is that if the STFT varies by more than 10% or so over a period of 30 seconds to several minutes, the LTFT is incremented or decremented so that the STFT is kept within the +/- 10% dynamic range. This allows the on-board diagnostic function of the ECU to monitor the LTFT against a pre-determined threshold. If the threshold is exceeded, the on board diagnostics will turn on the check engine light (CEL) and provide an error code related to the LTFT being out of range, indicating a possible problem with the engine (e.g. clogged fuel injector, bad HO2 sensor, oxygen leak in the exhaust system, etc.).

4.2. Cold Cranking Mode of Operation.

Cold cranking is that mode of operation when the engine is first started up and the HO2 sensor is not yet warmed up to operating temperature. In this mode of operation, the engine operates off of a fixed set of parameters in the engine control map of the ECU. When the engine is cold, the fuel that is injected does not vaporize well and exists in the cylinder as microscopic droplets of liquid fuel and not as a vapor. This means that only the molecules of fuel that are on the surface of each droplet can come in contact with oxygen from the air and burn. The fuel that is inside of each droplet cannot burn until the surface molecules are burned away. This condition requires a very rich air/fuel mixture to be introduced into the cylinder in order to provide enough surface molecules of fuel to provide sufficient power to crank the cold engine over. Older cars used a manual or automatic choke to create this overly rich mixture. The mixture was then (manually or automatically) leaned out to normal operation as the engine warmed up. Modern EFI engines use a set of values in the engine control map of the ECU, along with an engine temperature sensor input, to effect a similar operation.

The cold cranking mode of operation lasts only a very short while on any cold start, and represents a very small part of the overall engine operation. It is therefore acceptable to the EPA for it to be inefficient, as long as the HO2 sensor heats up rapidly and transitions the ECU into closed loop operation in a short period of time. While cold

cranking represents an insignificant period of engine operation, it is critically important. If the engine doesn't start, everything else is moot!

4.3. Wide Open Throttle Mode of Operation.

Wide open throttle (WOT) is the mode of operation that occurs when the driver presses down hard on the accelerator, e.g. for passing in a hill. In this condition, the driver wants the car to accelerate immediately; wants a surge of power, as opposed to the engine gradually building up power as it would in normal mode of operation. WOT requires an overly rich fuel mixture to ensure maximum combustion and to prevent the engine from getting too hot (rich cooling) and from fuel-starvation misfiring under heavy load. In older, carbureted engine designs, rapid depression of the accelerator would cause an *accelerator pump* to force a highly enriched air/fuel mixture into the intake manifold. This would ensure that the maximum amount of fuel was available to burn in the cylinder on the power stoke, even if a lot of the fuel was wasted in the process. The rapid change in manifold pressure would additionally activate a vacuum advance mechanism on the distributor to alter the normal ignition timing to prevent the engine from knocking during WOT. In modern EFI engines, the ECU senses the rapid depression of the accelerator (or the rapid opening of the throttle) and uses pre-determined values in the engine control map to immediately enrich the mixture and change the ignition timing as well. Consequently, the engine is operating open loop for the brief time that it is in WOT (until the driver eases off the accelerator). Like the cold cranking open loop mode, the WOT mode is inefficient from a fuel economy and pollution perspective, but this is tolerable as the engine is expected to be in WOT mode only for a very small part of its total operation.

4.4. Ignition Timing.

Closed loop operation permits a modern EFI engine to dynamically adapt to varying conditions affecting the proper air/fuel ratio for the normal mode of engine operation. During these variations, it is desirable to optimize the ignition timing as well. Some automobiles are fitted with knock sensors that detect inaudible engine knock, or other sensors that allow the ECU to determine optimum (just past knock) ignition timing on a dynamic basis. Such automobiles are able to set the ignition timing as advanced as possible without causing harmful and power robbing engine knock. The overall importance of ignition timing was described in section 3, above. The closer to the top of the power stroke that the pressure from the burning fuel presses down on the piston, the more mechanical energy will be delivered to the crankshaft. Automobile manufacturers that include these sensors on their engines do so to allow the driver to take advantage of varying grades and blends of gasoline that they may encounter. An engine that does not have this feature must run off of pre-determined base ignition timing settings and these settings (in the engine control map) must be such that the lowest grade conditions avoid engine knock. This necessarily means that whenever a higher grade (higher octane) fuel is used, the extra octane value cannot be put to best advantage in the engine. Of course, provisioning an engine with extra sensors adds production cost to the car, so there is a tradeoff that the manufacturer must consider. In general, all that can be said is that some automobile engines have a means to operate in a closed loop mode with respect to ignition timing and others do not. Those that do not are pre-programmed to accept the least common denominator of operating conditions and cannot take full advantage of superior conditions such as higher octane fuel.

4.5. Summary of Modes of Engine Operation.

The takeaway from this section is that a modern, EFI engine on an ordinary automobile that is designed to run on gasoline operates mostly in a closed loop mode of operation. In this mode of operation, the ECU is not dependent upon fixed air/fuel values in a map that has been pre-engineered with the assumption of a certain type of fuel. Rather, the ECU uses the HO2 sensor to dynamically keep the engine running at the optimal air/fuel ratio as determined by actual measurement and not based upon any assumptions. This factor is critically important in understanding what happens when ethanol is blended into gasoline in various mixtures, and how a flex fuel automobile is able to deal with high ethanol blends. It is also important that the open loop modes of operation not be

ignored. They are used only a very small percentage of the time, but when they are used, the ECU is running off of pre-determined parameters and is not able to adapt to differing fuel blends, unless special provisions are made to do so (as in a flex fuel vehicle). The next section discusses the impact of ethanol blends on both non-flex fuel and flex fuel vehicles in terms of these various modes of engine operation.

5. Effects of Ethanol Fuel on EFI Engine Operation.

The previous sections of this document pave the way for this section's discussion of the effects of ethanol fuel blends on modern, EFI automobile engines. Before diving into the technical details, it is important to understand a few basic facts:

> The U.S. EPA and the U.S. Department of Energy National Renewable Energy labs have certified E10 for use in all engines that are designed to run on regular, unleaded gasoline. In fact, all cars built and sold in the U.S.A. from 2001 on are warranted to run on E10 blends. You will not compromise your engine nor will you void your warranty by fueling your car with E10 (10% ethanol, 90% gasoline).
> The U.S. EPA and the U.S. Department of Energy National Renewable Energy labs have now certified E15 for all cars built in 2001 and beyond. Brazil has certified E25 (25% ethanol, 75% gasoline) for all cars in that country. This is an excellent indication that your car can run on higher ethanol blends than E10 or E15; however, Brazilian certification does not extend your U.S.A. warranty rights in any way.
> This section will also discuss engine modifications for making a non-flex fuel car into a car than can run any blend from pure gasoline to E85 (and even pure, hydrous ethanol). Technical information and theory notwithstanding, it is not legal to modify your car's engine for street use unless the modification is approved by the EPA (CARB, in California). EPA (and CARB) approvals are granted on the basis of a specific modification to a specific car model (or at least a specific power train). Some modification kit manufacturers claim that their kits are "EPA certified" but the EPA does not certify a "kit". It only certifies a modification, meaning a specific kit installed in a specific model car with a specific power train in a specific way. There are some approved modifications, but not many. You may still modify your car's engine if you choose, but the modified car may not be legally driven on the streets.

5.1. Ethanol Fuel and non-FFVs.

This section discusses what happens if you add ethanol to gasoline for your EFI, but non-flex fuel vehicle (non-FFV). Section 2 presented information about the chemistry of gasoline and ethanol. Section 3 discussed electronically controlled fuel injection and presented the fundamental difference between ethanol and gasoline as far as your non-FFV engine is concerned: the significant difference is stoichiometric ratio. Recall that the stoichiometric ratio for regular gasoline is approximately 14.7:1 and that for pure ethanol is around 9:1. What this means, in simple terms, is that if you fill up your tank with a high ethanol blend and start the car up in normal operation, it will initially be running very lean. If the car is warmed up and running in the normal operating mode, it will immediately be in closed loop mode and the HO2 sensor will so signal the ECU. The ECU will, in turn, start increasing the fuel trim to richen up the mixture. As long as the fuel pressure and fuel injector range is sufficient, the ECU will richen up the mixture to where it is pre-programmed to be (recall: a little richer than stoich) and the engine will run fine; at least for ten minutes or so. TheAutoChannel.com (www.theautochannel.com) says that they test all new cars, non-FFV and FFV alike, on E85 and they all run fine (in normal, closed loop mode). This should not be a surprise, based upon the technical information in sections 3 and 4, above. Recall that in closed loop operation, the ECU does not rely on pre-determined notions of how the fuel mixture should be controlled; the mixture is dynamically adjusted based upon actual measurement of the lambda of the mixture being burned in the engine. Recall that lambda is a measurement of the relationship of the actual mixture to stoich, as measured by the HO2 sensor and independent of what the actual stoichiometric ratio is for the fuel. Therefore, in closed loop

operation, the ECU does not know, nor does it care, what the stoichiometric ratio for the fuel is, as it is provided with the lambda value to optimize on.

There is, unfortunately, one problem. Recall that the EPA requires that emission controls operate correctly for the life of the vehicle and that on-board diagnostics are required to inform the driver if the ECU senses a condition wherein the emission controls may not be working correctly. One required condition is where the long term fuel trim (LTFT) gets too large. The definition of "too large" is up to each automobile manufacturer to determine, but it is often the case that a tank full of E85 will cause the LTFT to exceed the predetermined threshold and turn on the *check engine light* (CEL). Note that the LTFT takes time to build up (the ECU requires time to move STFT to LTFT). Therefore, the CEL does not come on immediately and you may have to drive for 10 – 30 miles before it comes on due to this cause.

If you have been following the theory presented in the paper, you will know that this can be an artifact of the ECU's software not being "ethanol-aware" when, in point of fact, there is nothing actually wrong with the engine. Nevertheless, it is definitely not recommended that you drive your car around with the CEL on because you have no way to know if this is an artifact or if some serious problem has been detected (or if your EFI system cannot sufficiently compensate for high ethanol blends). Even if you purchase a diagnostic readout device and check the error code(s) to see that the CEL is related to LTFT, you have no positive proof that your engine is operating OK unless a mechanic checks out all of the possible abnormal causes of the error, per the car's service manual, and determines that everything is OK (the folks at TheAutoChannel.com claim to have done this).

Some people have questioned whether the fuel pump, fuel pressure regulator and fuel injectors have the range to adapt all the way to E85 or even E100. Obviously, the answer to this question depends upon the specific power train of the car. But do note that the open loop modes of operation (cold cranking and WOT) require a highly enriched mixture. If the car runs well under these conditions, it is a pretty good indication that sufficient fuel injector range is available for normal operation, even with high ethanol blends.

While an automobile engine spends almost all of its time in normal, closed loop operation, the cold cranking mode is the mode that starts a cold engine. The normal operation mode is moot if the engine does not start. Also, WOT operation is open loop and the engine can overheat (potentially causing serious engine damage) and/or misfire if the mixture is not sufficiently enriched. These modes of operation are open loop and controlled by pre-programmed settings in the ECU. A non-FFV ECU will use the settings for gasoline and may not enrich the fuel mixture sufficiently for the car to operate well in these modes. This is not an issue with E10, E15 or perhaps even E25, but may be an issue at E50, E85, or E100. Again, it depends upon the car and no generalizations are possible. It is therefore possible that if you fuel up your unmodified, non-FFV with a high ethanol blend, it will start and run OK when warm, but will hesitate on hard acceleration and/or may experience starting problems on a cold morning. Since ethanol has a lower combustion temperature than does gasoline, the possibility of heat damage due to insufficient enrichment is not likely in most unmodified vehicles.

A word about ignition timing is in order here as well. It was mentioned in section 4 that some EFI engines have knock sensors and determine optimal ignition timing dynamically, while other EFI engines do not have such sensors and use static, pre-programmed settings. The base ignition timing for gasoline will be significantly retarded compared to the optimal setting for a high ethanol blend. This is due to two factors: (1) ethanol burns slower and cooler than gasoline, and (2) ethanol is very high octane and can ignite much closer to top dead center (more timing advance) than would be safe for low octane gasoline. It is not possible (not practical, anyway) for a vehicle owner to adjust ignition timing on an EFI engine, as it was on the older carbureted engines. The ignition timing is all controlled by software in the ECU. It will not harm the car for the timing to remain retarded, but the engine will not realize the full potential of power and fuel mileage offered by ethanol's high octane rating.

Before concluding the discussion of high-ethanol blends on non-FFV engines, a few other issues should be discussed:

Fuel system corrosion: you will read in many places that ethanol is more corrosive than gasoline. This is a somewhat misleading and inflammatory statement. Ethanol is an excellent solvent and will certainly attack substances that are unaffected by gasoline. Ethanol is also miscible in water and any water carried by ethanol fuel may corrode parts of the fuel system. However, ethanol designed to be blended with gasoline must be dried (anhydrous), so water should not be a problem, unless the fuel is sitting around exposed to the atmosphere for long periods of time. The bottom line here, though, is that the E10 standard has been around since the 1990s, and automobile manufacturers have had to address these issues even with a low ethanol blend. Consequently, most any EFI vehicle, and certainly one built in 2001 or later, will have ethanol tolerant components in the fuel system. Consequently, corrosion is generally not a practical concern.

Vapor lock: you will find claims that ethanol will cause vapor lock in a non-FFV owing to its Read Vapor Pressure rating. Any EFI fuel system is already sealed for evaporative emission control (EVAP) and this prevents vapor lock, whether for gasoline or ethanol or any other fuel for that matter.

Phase separation: ethanol is miscible in water and gasoline is not. It has already been mentioned that ethanol must be dried in order to mix with gasoline. If the mixture then comes in contact with water, the ethanol will "bond" with the water (figuratively, not chemically) and, if the water content gets above a few percent, the ethanol-water mix will separate out from the gasoline (*phase separation*). The resulting ethanol-water mix will be high in ethanol content and the gasoline part will be low in ethanol content. Some people claim that this will have no effect on engine performance, based upon the discussion of closed loop operation, above. However, problems with cold start and WOT, which are open loop modes, could then be expected to occur if the fuel phase-separates. Fortunately, pollution control laws already require that fuel tanks in gas stations and those in the cars be sealed systems and water contamination is not a real-world issue. However, this is not true of fuel that is stored in an unsealed gas can or other containers, as may be the case for lawnmower engines and marine engines. This aspect is addressed further in section 6, below.

Fuel line clogging: Ethanol is an excellent solvent. Gasoline has lots of impurities in it. An engine that has been running on gasoline for a long time (say 40,000 miles or more) may have a varnish of gasoline impurities coating the fuel system components. If ethanol is then placed in the gas tank, it may dissolve off the varnish which will travel, in clumps of gunk, into the fuel filter and clog up the fuel system. Once again, automobiles built in 2001 or later will have some protection against this varnishing action. For older cars, it is recommended that ethanol be blended into the gasoline in steps and that the fuel filter be replaced after the highest operating blend is reached.

In summary, increasing the ethanol blend beyond E15 in an EFI engine that is not an FFV will, in all likelihood, cause no damage to the engine and little or no degradation in performance (the performance might increase, in fact; particularly if the EFI can dynamically adjust the ignition timing to make better use of ethanol's very high octane rating). The fuel mileage will likely suffer because ethanol is an oxygenated fuel and, particularly, if the ignition timing is not dynamically alterable, but some studies have shown slightly increased mileage. If the percentage of ethanol is high enough, the CEL will come on in many cases. It has been widely reported that mechanics are charging motorists who inadvertently fill their non-FFVs with E85 many hundreds of dollars to drain and dry out the fuel system. This is totally unnecessary, as long as the motorist is OK with driving around with the CEL on for a half tank of fuel or so. The engine will run well in normal operation, but may have some starting problems on cold mornings and may misfire and overheat when accelerating very hard. But otherwise, the engine is OK, and more so if hard acceleration is avoided during this period. After burning off about half the fuel, adding regular gasoline (or E10) will bring the blend up to < E50, which should turn the CEL off. Some ECUs latch the CEL, in which case it may be necessary to pull the negative battery cable for 10 seconds to reset the ECU's stored values. After the car is

restarted and driven for a few minutes, the CEL should reset itself. No damage will occur during this time, unless another problem comes up while the CEL is being ignored.

5.2. FFV Operation and Theory.

The original, modern, flex fuel vehicle (FFV) was developed by engineers at Ford Motor Company in the 1980s. Ford, at the time, was working with the California Energy Commission to develop automobiles to run on cheaper, domestic fuels (cheaper than oil, whose price had just been run up, for the second time, by OPEC). The California Energy Commission was, at that time, interested in *methanol* and Ford built several hundred (later thousands of) automobiles modified to run on methanol, for testing in California State fleet vehicles. These vehicles all had EFI engines and the Ford engineers were able to develop engine control maps that were optimized for methanol. The cars all ran well and showed improvement in life span over their gasoline powered equivalents. However, the cars could only be fueled at the limited number of methanol pumps then installed at state fleet facilities. Long range trips were not possible. The engineers then went back to the lab and created an ECU program that had maps for both gasoline and methanol and the ECU software was modified to interpolate between the maps based upon the mixture of methanol and gasoline in the vehicle's fuel tank. The fuel mix was dynamically determined by an additional *fuel composition sensor* that was added to the fuel tank and whose signal was monitored by the ECU. These early FFVs worked fine and established the design principles by which all FFVs operate today – with one exception, that is. The fuel composition sensor added several hundred dollars to the production cost of these vehicles. Although some manufacturers continue to use fuel composition sensors in FFVs today, Ford (and others) no longer does so. A software algorithm (running in the ECU) now determines the composition of the fuel without the need for any additional sensors.

In order to understand how a software algorithm can determine fuel composition, it is necessary to recall that any modern EFI engine, even in a non-FFV, dynamically monitors the air/fuel mixture (the lambda) and that the long term fuel trim (LTFT) value stored in the ECU reflects the fuel injector timing adjustments necessary to achieve the pre-determined lambda. Recall that putting a tank full of E85 in a non-FFV may eventually turn on the CEL, owing to the LTFT exceeding a diagnostic threshold. If the ECU software is "smart enough" to notice that fuel has been added to the tank (which it can do by monitoring the fuel level indicator), and then upon sensing a fill-up, if the ECU software then monitors the LTFT and notices that it increases or decreases monotonically for a several miles of driving and then levels off, the software can almost certainly declare that the LTFT change was due to a change in the fuel mix, and the absolute value of the LTFT change determines the new fuel mixture (the change from the previous fuel mixture). In order for this algorithm to work, the driver must: (1) add a significant amount of fuel to the tank when changing fuel mixture, so that the ECU can notice the change, and (2) drive the car warmed up for 10 miles or so. This is, in fact, the recommendation found in the Ford FFV owner's manual.

You will often see statements to the effect that an FFV adds $100 to $200 to the production cost of a car. This is obsolete information. Today's non-FFVs contain exactly the same hardware as the FFV equivalents, for those manufacturers who use the software method of determining fuel composition. The production cost difference is almost exactly zero. Yes, there are one-time costs associated with *production engineering* a change from a non-FFV to an FFV: the development of design, testing, assembly instructions, documentation, provisioning and stocking plans, etc. But once these costs are absorbed, the cost of production of the FFV is identical to a non-FFV. This is why automobile manufacturers have, in recent years, simply manufactured various power trains as FFV only. The older idea of having non-FFV and FFV versions of the same power train simply increased the manufacturer's logistic costs without any decrease in the all-important production cost.

Regardless of whether the ECU determines the fuel composition via a hardware sensor or a software algorithm, the ECU can determine open loop fuel mixture and base ignition timing by interpolating between engine control maps for gasoline and alcohol using now well-understood interpolation functions. The FFV ECU runs the engine at optimal engineering conditions under any mixture of alcohol and gasoline. Of course, the fuel system components

must be ethanol tolerant, but with the E10 standard in play, most non-FFV fuel systems are already ethanol tolerant and no material changes are required.

5.3. Conversion of non-FFV EFI Engines to FFVs.

There are over 200 million automobiles with non-FFV EFI engines on American roads today. While an FFV does not cost any more than a non-FFV, the choices of FFV vehicle are still limited and most people will not buy a new car just to get an FFV anyway. There is, therefore, a growing interest in converting a non-FFV to an FFV.

The discussion above should be sufficient to prove that a non-FFV can be converted to an FFV by changing out the ECU for one programmed to be an FFV. This assumes that the vehicle's fuel system meets the requirements for an FFV, which most recent ones do. Unfortunately, there do not seem to be factory certified, drop in replacement ECUs available. Certain powertrains are available from the factory in both non-FFV and FFV versions. In these cases, it might be possible to convert a non-FFV to a true FFV by purchasing and installing FFV-version parts (including the FFV version ECU) as replacement for the non-FFV parts of the fuel system, wherever they differ.

Aftermarket, field programmable ECUs do exist, mainly for racing enthusiasts. There is also an open source software movement creating software (based upon standardized microcontrollers) for these aftermarket ECUs (see http://www.diyefi.org for further details and information). However, it appears (at the present time, at least) that a great deal of technical expertise and exotic equipment is required to program one of these units to convert a standard EFI vehicle to an FFV. Furthermore, it does not appear that (at present) there are any EPA certified conversions to FFVs using aftermarket ECUs.

The effect of putting E85 in a non-FFV was discussed above. The major issue is the CEL coming on, with additional issues related to operation in the open loop engine modes (cold cranking and WOT). An Internet search for "flex fuel conversion" will result in links to manufacturers of FFV conversion kits. What most of these kits actually do is to receive the fuel injector pulses from the ECU and lengthen them. If the pulse length extended by these kits is sufficient, the ECU's LTFT will never reach the diagnostic threshold that causes the CEL to come on. This, in effect, "converts" the non-FFV to an FFV, albeit these kits are probably better described as "cheaters" rather than "converters" because they "cheat" the ECU into thinking that the needed fuel trim is less than is actually applied, as opposed to actually "converting" anything.

The biggest benefit of these converters (or cheaters) is the simplicity of installation and operation. The kits consist of a small electronic module with a number of electrical cable sets emanating from them. There is a one-to-one correspondence between the module's cable sets and the number of fuel injectors in the engine that is to be "converted". The electronic module is mounted at some convenient location in the engine compartment. Each cable has a male and female connector that is the same type as on the fuel injectors in the engine. To install the kit, the cable from the ECU to each fuel injector is disconnected from the injector and plugged into one of the mating connectors of the module's cables. The corresponding connector is then plugged into the injector from which the ECU's cable was removed. The only other connection is to ground the module by attaching a wire to the battery negative or just the car frame. As long as the engine's fuel injectors are easily accessible (not always a good assumption!), installation of the kit can be performed by someone without any specialized tools or technical know-how and without cutting into anything on the engine.

There appear to be two general types of conversion kits on the market today. The difference is in how the module determines how much pulse time to add to the fuel injectors. The lower cost converters require the driver to set a potentiometer (*pot*) depending on the fuel mix in the gas tank. This is not as bad as it sounds, because the setting is not particularly critical. Recall that the ECU is actually adjusting the fuel trim in a closed loop operation with the HO2 sensor. If an intervening device adds some time to the injector opening, the closed loop operation will still work normally with the ECU performing the fine adjustments dynamically. Recall that the purpose of adding pulse

time to the injectors is simply to keep the LTFT lower than the threshold that causes the on-board diagnostics to be fooled into thinking that there is a problem with the engine. So as long as the extra pulse time is less than what the actual injector pulse time needs to be, the engine will work fine. It is, however, necessary for the driver to remember to reset the pot to zero if the car is filled with gasoline; otherwise, the convertor kit may hold the injectors open longer than the total time that the ECU determines is correct (making too rich a mixture and throwing a diagnostic error code the other way).

More expensive convertor kits do not have any manual adjustments and operate automatically. These kits appear to have a small computer inside of them that is programmed to mimic the ECU's actions of converting STFT to LTFT, as described in section 3, above. The kit's computer averages the injector times from the ECU over periods similar to what the ECU does, staying slightly ahead of the ECU in this regard. In lieu of the ECU adding to or subtracting from the LTFT, the kit adds or subtracts a little from its output injector pulse time, effectively keeping the ECU's LTFT out of the equation by adding in the kit time to the ECUs STFT in lieu of the ECU adding LTFT to STFT.

Regardless of the strategy used by these convertor kits to alter injection pulse width, the kits do not change the ignition timing. Consequently, they cannot do everything that an FFV ECU would do to optimize engine operation for high ethanol blends. The ECU of the "converted" non-FFV will still compute ignition timing from base values in its engine control maps that were programmed to optimize ignition timing for gasoline (unless the engine has knock sensors and optimizes ignition timing dynamically). This is one reason why these cheater kits are not usually as effective a conversion strategy as a reprogrammed ECU.

The other issue with cheater kits is that they may or may not help with the open loop modes. Recall that in cold cranking and WOT operation, the ECU ignores the HO2 sensor readings and uses data from its engine control map to control fuel injection timing. The non-FFV map is engineered for gasoline. Some cheater kits have an engine temperature sensor that tells the kit's computer that the engine is cold and uses this information to add pulse time to the injectors in cold cranking mode. A kit with a pot setting determines the desired cold cranking fuel mixture from the pot position (required for proper open loop injector timing setting). This will work but the pot setting is now significantly more critical than it is in closed loop (normal) engine operation. A kit that does not have a manual pot setting must remember (in a non-volatile memory) what the fuel mixture is, based upon its own prior determination of LTFT. In this sense, the aftermarket conversion kit continues to mimic what the FFV ECU does (the ones that don't rely on a fuel composition sensor). Of course, the conversion kit does not have sensor inputs for the fuel level, so the kit cannot determine that the engine has been refueled. Furthermore, neither type of kit can be expected to handle WOT mode very well, as they do not have input from the throttle sensor or the air intake mass sensor. The best that such a conversion kit can do is to see that the ECU is suddenly and drastically increasing injector time and infer that this means WOT mode. The kit can then infer the fuel mixture (if so equipped) and add additional injector pulse time accordingly. But again, the kits do not control ignition timing, albeit a high ethanol blend is much less likely to cause the engine to knock under WOT operation than is gasoline.

There is one final, non-technical, consideration with aftermarket cheater kits. Only a few engine conversions using these kits have been approved by the EPA. This is a technical paper and does not deal with the legal issues, but the reader is cautioned to check these issues out before modifying their car engine in a way that might not meet legal/regulatory requirements.

6. Effects of Ethanol Fuel on non-EFI Engines.

A final topic addressed by this paper is the effect of ethanol fuel on non-EFI engines. These engines generally fall into the categories of small, often 2 stroke, engines (lawnmowers, leaf blowers, chain saws, motorbikes and small motorcycles), marine engines and classic car engines.

These types of engines are generally carbureted, vs. EFI, designs and as such, are inherently not automatically adjustable. They have no such operation as the normal closed-loop operation of a modern automobile engine. They are designed for use with gasoline and if ethanol is blended into the gasoline, the engines will run lean (unless they are recalibrated on the ethanol blend being used).

A substantial number of people attribute lean engine operation to overheating and engine damage. This is certainly true for an engine running lean on gasoline. Ethanol, however, burns much cooler than gasoline and the extra oxygen atom in the fuel adds mass to the burning gasses that increases mechanical efficiency of the engine. Therefore, there is something of an offsetting effect. It is very hard to generalize over the wide range of engine designs covered by this short section. EPA/DOE testing for E10 and now E15/E20 has not found a problem with these low-ethanol blends with any of a wide variety of small engines that have been full lifecycle tested. As the ethanol content is increased, there may or may not be a point where the engine operating temperature gets too high and potentially damages the engine. Beyond this point, the engine will run cool and lose significant power (the engine can't run on just air, after all). Of course, if a fixed ethanol blend is expected, a carbureted engine can always be modified to run optimally on that blend. This requires some mechanical skills, but recall that the first automobiles (carbureted engine designs) ran on pure hydrous ethanol and that early Ford model T's were actually a kind of FFV, albeit with manual controls for mixture and ignition timing adaptation.

Concern has also been expressed about lubrication of 2 stroke engines, since 2 stroke engines require the lubricant to be mixed in with the fuel. Some 2 stroke engine manufacturers recommend using a special, synthetic oil in lieu of petroleum-based engine oil. However, other manufacturers do not. There is nothing inherently wrong with mixing anhydrous ethanol with petroleum based oils anymore than there is with mixing anhydrous ethanol with petroleum based gasoline. However, if enough moisture gets into the fuel/oil mixture to cause phase separation, then engine lubrication may be compromised. Additionally, ethanol may not be compatible with additives used in various lubricants. The manufacturer's recommendations should be followed in all cases. There is, of course, a problem if you want to run a higher ethanol blend in your small engine than the manufacturer has recommendations for. In all, it is best to simply avoid this.

Small engines and, particularly, marine engines have the problem that the engine is run on a much less frequent schedule than an automobile engine. They also have the problem that the engine is usually not fueled directly from the pump (you can't drive your leaf blower to the gas station, although you can carry it there). Frequently, the fuel is stored in a gas can or some other container, usually in an open space that is not well protected from moisture. This is even more true for marine engines, which operate in an inherently moisture rich environment. The concern about moisture induced fuel and lubricant phase separation is quite valid here, although it can be avoided with proper storage procedures and equipment.

The best advice for all of these types of engines is to stick with gasoline. EPA/DOE testing on E10 (and now E15/E20) has been thorough in this regard and engine manufacturers are required to give recommendations about running their engines on these blends. Beyond E15, it is probably best to separate fuel for these types of engines from fuel for automobiles. Collectively, automobiles consume over 200 billion gallons of fuel per year (in the USA). Small engines and marine engines consume a very tiny fraction of this amount. There simply are not the same economic, security, supply and environmental issues with these engines as there are with automobile engines. Use of blender pumps at filling stations will nicely resolve this issue, as low ethanol blends can always be found when needed. This applies to classic cars with carbureted engines as well. If you want to run your carbureted engine on high ethanol blends, you will have to convert the fuel system to do so. Extensive information about carbureted engine conversion can be found in the book "Alcohol Can Be A Gas" by David Blume (ISBN 9780979043789 hardbound; 9780979043772 paperback) (see http://www.permaculture.com for details).

7. Summary and Conclusions.

Ethanol was the original fuel for automobiles and was also extensively used as an octane booster for low grade gasoline. Ethanol is an excellent motor fuel that burns much cleaner and more efficiently then does gasoline. Anhydrous, or dried ethanol, blends well with gasoline and ethanol-gasoline blends are increasingly common, even mandated by various government actions. The current standard in the USA is E10, which is 10% ethanol and 90% gasoline. A change to E15 should be implemented shortly. E10 and E15 will work in any automobile and have been tested to not harm small 2 stroke and marine engines. Brazil has an E25 standard and it is possible that E15 is not the limit for unmodified engines in the USA in the future. In the meantime, the USA and some EU countries have adopted an E85 standard (85% ethanol, 15% gasoline) for flex fuel vehicles (FFVs), while Brazil goes all the way to pure ethanol (E100).

Ethanol is an oxygenated fuel and has a lower stoichiometric ratio than does gasoline. The air/fuel mixture must be significantly enriched when running an engine on high ethanol blends. Modern, electronically fuel injected automobile engines run in a closed loop mode of operation under normal conditions and can adapt to higher ethanol blends with no problem. Ignition timing should be altered for high ethanol blends as well. Some modern automobiles can dynamically adapt their ignition timing while others cannot. However, ignition timing adjustments for high ethanol blends are less critical than air/fuel mixture adjustments (ignition time is very critical when going from a tuning for high ethanol back to gasoline). Automobile engines also have open loop modes of operation and the engines will not adapt to high ethanol blends in these modes of operation, but workarounds are possible.

Flexible fuel vehicles (FFVs) were invented in the 1980s and today's FFV designs use exactly the same hardware as do modern non-FFVs. Only the software in the engine control unit (ECU) is different. A modern non-FFV may be converted to an FFV by an appropriately programmed aftermarket ECU; however, these are not openly available for street vehicles and may violate various laws and regulations if used for other than specialized (e.g. racing) purposes. Aftermarket "cheater" kits are simple to install and can compensate a non-FFV engines for high ethanol blends, either with a simple manual setting or automatically. However, these kits do not change ignition timing and may not fully compensate open-loop modes of engine operation. Furthermore, the kits are only certified by the EPA for certain specific power train conversions and may not be legal for converting other power trains.

Small, 2 stroke and marine engines have additional issues with high ethanol blends. They may be adapted to run well on specific blends but are not generally able to be made "flex fuel" and are best run on a specific blend at all times.

In conclusion, most automobiles on the road today could run on high ethanol blends if legal, certified conversion kits (best: aftermarket ECUs) were available. Ethanol is a renewable, clean, domestically produced motor fuel and, as such, can solve many of the nation's economic, political and environmental problems. As an alternative fuel, ethanol (and other alcohols) is superior to all other alternatives because it is easy and inexpensive to manufacture FFVs and to convert non-FFVs to FFVs. The national fuel distribution system is geared towards the production, storage and distribution of liquid fuel. The production cost of a new FFV is essentially identical to a non-FFV of the same model. FFVs require no additional fuel tanks or other space and weight hogging equipment, and do not present the driver with any compromises vis-a-vis the familiar gasoline powered engine. The vehicle performs the same on ethanol as on gasoline and can always be fueled on gasoline if ethanol is not available. Every mechanic already knows how to repair an FFV; every auto parts store already carries parts for an FFV; every driver already knows how to fuel, operate and maintain an FFV. This cannot be said for any other alternative fuel option. There only needs to be the political will to remove the barriers to widespread use of alcohol fuels in automobiles. Change can then happen in a very short period of time and with essentially no pain to the consumer.

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